Switched Photonic Delay Lines for True Time Delay Antenna Beam Steering: Technologies and Challenges

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Abstract. In military applications, conventional antenna systems are typically designed to operate in either transmit or receive mode, and are typically fed electronically with a coaxial cable from the processing station. Such electronic feeds entail high loss, are heavy, and significantly degrade the size, weight and power (SWAP) efficiencies of the link. Photonic technologies on the other hand are very attractive for application in antenna systems due to their low loss, lightweight flexible cabling, immunity to electromagnetic interference, broad bandwidth, and overall ability to antenna remoting over distances not possible with conventional electronic approaches. One critical system in military applications is the photonic based beam-steering and in particular photonic delay lines (PDL). PDLs are powerful alternative and important technology for implementation of wideband PAA controllers since they solve many of the above mentioned limitations of electronic controllers. PDLs are key components to develop a future, wide bandwidth, compact, lightweight and small size, PAA controller. Furthermore, PDL provides parallel processing capabilities that can lead to compact and lightweight processing modules, which is of high importance to military applications. A variety of photonic switching approaches have been proposed to implement PDLs. Different photonic technologies include laser switching, acousto-optics, liquid-crystal devices, micro-electro-mechanical-systems, semiconductor optical amplifiers etc. In this paper we review and evaluate how the different photonic technologies can address the phased array antenna needs. Emphasis is given to photonic switching with semiconductor optical amplifiers, as well as photonic delay elements based on fiber optic circuits that required to satisfy the phased array antenna requirements, as well as the challenges ahead.

Keywords: Photonic delay lines, optical beamformer, photonic control of phased array antennas, photonic switching, sensor arrays.

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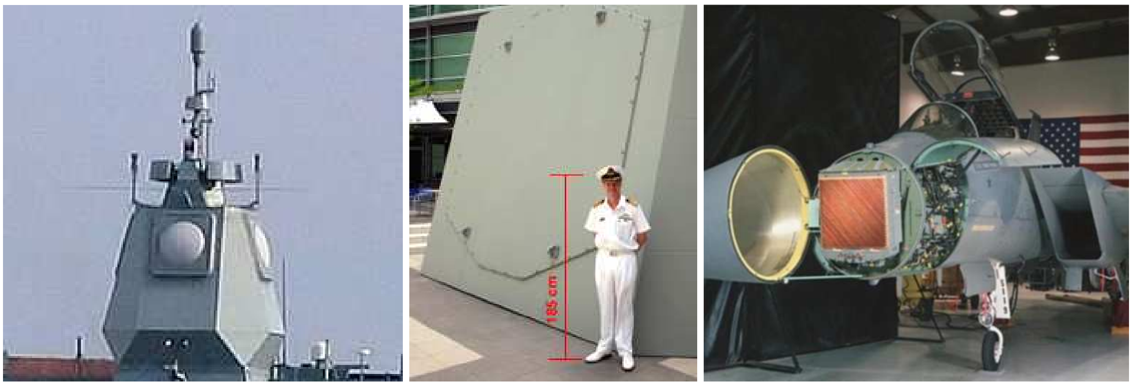
INTRODUCTION

Unlike large mechanically steered antennas, such as dish or parabolic antennas, active phased array antennas (PAAs) offer many advantages, including beam steering without physical movement, highly accurate beam pointing, and increased beam scan flexibility in three dimensions (3-D). Presently, most PAAs are used for military applications as electronically controlled PAAs are extremely expensive for large scale commercial use Fig. 1).



(a) (b) (c)

FIGURE 1: (a) Active Phased Array Radar mounted on top of Sachsen class frigate F220 Hamburg's superstructure manufactured by Thales Nederland [1]. *(b)* Aegis combat system in the USS Pinckney (DDG 91) [2].

To detect small objects using a phased array radar, very short microwave frequency pulses are used, and thus wideband antenna control is required. At present, this is a difficult task for electronic based controllers. In addition, broadband phased array radars require long time delays. Nevertheless, long time delays cannot be implemented using electronics due to the frequency sensitive, heavy, lossy, and power consuming nature of microwave waveguide-type delay lines.

Photonic processing can offer significant advantages at high frequencies (e.g., microwave and millimeter-wave bands), such as (a) large instantaneous and tunable signal processing bandwidths (several GHz), (b) immunity to electromagnetic interference (EMI) and electromagnetic pulses (EMP), (c) lower module weight, (d) lower power consumption, (e) less frequency sensitivity and lower energy. Photonics also provides parallel processing capabilities that can lead to compact and lightweight processing modules. In a photonic approach, remote control of the PAA can be accomplished using the low loss optical fibers to transmit the signal from the controller site to the antenna site. Hence, PDLs are key components to develop future, wide bandwidth, compact, lightweight and small size, PAA controllers. This becomes even more important as broadband PAA systems start moving from sea borne to air borne applications as well (Fig 1(c)).

PAAs have features that are highly desirable for many emerging commercial applications such as cellular communications, satellite communications, air traffic control radars, and other mobile platform antenna systems [3-6].

In this paper, we present different photonic technology approaches for the implementation of photonic controllers for phased array antennas and we comment on the limitations and the strong points. At the same time we offer an alternative approach that uses semiconductor optical amplifier and Optiflex technology to simultaneously overcome propagation loss, fast switching response, and accurate differential delay control.

PHASED ARRAY ANTENNA CONTROL SCHEMES

The PAA has an aperture that is assembled from a great many similar radiating elements, such as slots, dipoles or printed circuit “patches” [7, 8]. Each element is controlled individually in phase and amplitude. Accurately predictable radiation patterns and beam directions can be achieved by varying the relative phase difference and the amplitude of the signal that drives the radiators (antenna elements). Phased arrays have the potential of operating over very wide bandwidths. The high end of the frequency band is limited by the physical size of the elements, which must be placed close enough in the array to avoid the generation of grating lobes [7]. A radar system that has the ability to change frequency over a wide band can adapt its transmission to take into account frequency-dependent multipath characteristics, target response, environmental conditions, interference and jamming [7]. Moreover, wideband processing can give fine range resolution. Phased array antennas break the conventional nexus between the aperture size and the spatial resolution [8] and thus have been used for military applications as well as for radio astronomy. Smaller overall size systems allow the fine spatial resolution required in advanced radar applications that would be impossible to be obtained using conventional radar systems where the required aperture size would be limiting. In addition, phased array antennas can track many targets simultaneously on a time-sharing basis. Thus, phased array antennas can be used for air traffic control applications. Mechanically steered antennas/radars waste time to point the beam from target to target. On the contrary, the inertia-less beam of a phased array antenna can "jump" from one point in space to another in microsecond (μs) speeds, and it may widened or narrowed at microsecond (ms) speeds, thus providing a great amount of agility [9].

The phenomenon of steering a phased array beam is the result of the energy from each element adding in phase at some desired point. Thus, the desired scan direction can be obtained by selecting a relative phase difference between the antenna elements. If the phases of all antenna elements are equal, the resulting beam points in the direction of the aperture's boresight axis. Different beam directions can be obtained by applying the appropriate phase sets to the antenna elements. Since the phases can be changed electronically, and in our case photonically, an inertia-less beam is formed that can be directed at any direction within the field of view of the array aperture. PAAs can employ two types of control techniques for scanning an antenna beam. The first technique is called phase-based scanning and uses modulo-2π phase shifters to set the phase of the microwave signal that drives the antenna elements. This technique is frequency sensitive, and causes beam squinting when the instantaneous bandwidth of the signal exceeds a certain value while using a fixed phase setting [7]. The second technique is called true-time delay steering and is frequency independent. In this technique, delay lines are used to give different time delays to the signals and allow wideband signals to be radiated from the antenna elements without beam squinting [7]. Array lengths of several hundreds of λ or higher is quite common in many practical applications. Because of the requirement that $d \le \lambda_{min}/2$, a large number of array elements are necessary in those large arrays. Unequally spaced linear array is developed mainly to reduce the number of array elements while keeping a comparable performance [10-12].

Phase-based Steering

When energy is incident at a phased array at an angle θ (Fig. 2a), the incremental phase shift ϕ required between adjacent antenna elements for a scan angle θ is given by [7]

$$\phi = \frac{2\pi}{\lambda_{RF}} \cdot d \cdot \sin\theta, \tag{1}$$

where λ_{RF} is the wavelength of the emitted RF signal, and d is the inter-antenna spacing. This indicates that the required phase is frequency dependent. If the microwave frequency is changed and the phase setting of the phase shifters is not changed the beam will move. Thus, any change in frequency (instantaneous or tunable) will cause the beam to deviate from the desired scan positions. This is called beam squinting and can be described [7] by

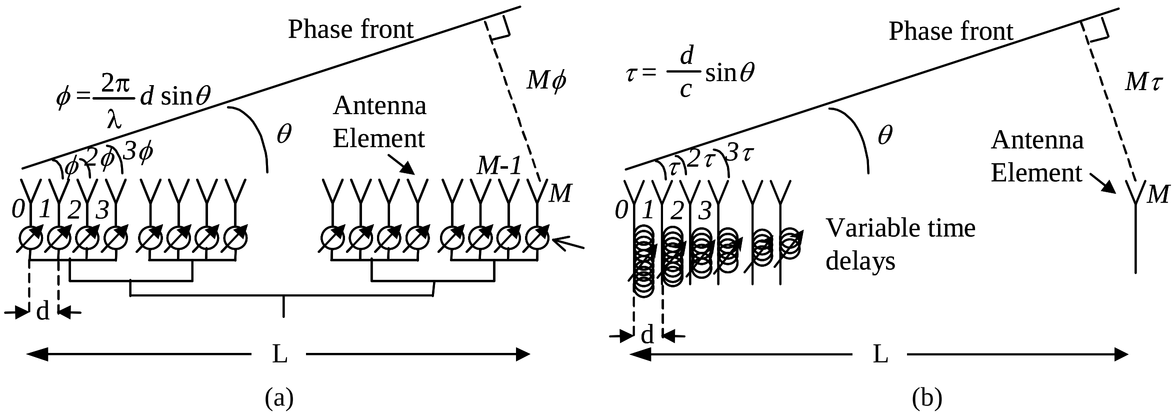


FIGURE 2. (a) Schematic representation of a phased antenna array with phase based control; (b) PAA with time delay based control. One dimension is shown for simplicity.

$$\Delta\theta = \frac{\Delta f}{f} \cdot \tan\theta \,, \tag{2}$$

where $\Delta\theta$ (in rad) is the change in the scan direction, f is the frequency of operation, Δf is the change in frequency and θ is the desired scan angle.

True Time Delay Steering

To prevent beam squinting, while maintaining large instantaneous bandwidths, the modulo-2π phase shifters must be replaced by time delay networks (Fig. 2(b)). The total delay path length that has to be provided amounts to $L \cdot \sin\theta_{max}$, where θ_{max} is the maximum scan angle for the aperture L. The incremental time delay is

$$\tau = \frac{d}{c}\sin\theta \,, \tag{3}$$

where d is the inter-antenna spacing, c is the velocity of the electromagnetic radiation in air, and θ is the incremental scanning angle. A typical schematic diagram of an electronic time delay network is shown in Fig. 3. The signal is routed via electronic switches through the N-delay paths whose length, and thus time of propagation, increase successively by a power of 2. Since each switch allows the signal to either follow the delay path or the non-delay path, a total delay T can be inserted. This delay T can take any value from 0 to $(2N - 1)\cdot \tau$, in increments of τ. Note

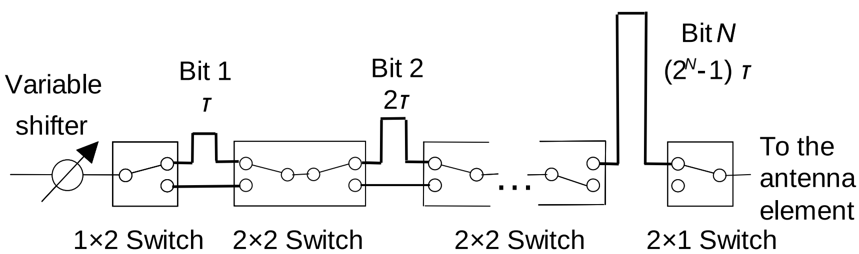


FIGURE 3: A typical N-bit switched time delay line network that requires N-1 2×2 switches to implement the 2^N different time delay settings. Signal in each bit can follow either the delay or non-delay path; a microwave phase shifter provides the fine modulo-2π phase control.

that binary algebra can be followed to calculate the obtained delays. In general a time delay can be described by

$$Ti = (b_{0i} \cdot 2^0 + b_{1i} \cdot 2^1 + ... + b_{Ni} \cdot 2^N) \cdot \tau, \quad (4)$$

where b_{0i}, b_{1i}, ..., b_{Ni} are switching factors that take the value of 0 or 1, depending on whether or not the signal follows the non-delay (for “0”) or delay (for “1”) path respectively.

Beam Shaping

Although steering capability is the most common function, a PAA can also provide beam-shaping capability by appropriate arrangement of the feed signals. A radar system with variable beam-width can produce a wide beam for the acquisition of targets and a narrow beam for subsequent high-precision tracking. Additionally, a broadcast satellite antenna with variable beam-width can achieve efficient coverage of irregularly shaped geographical service areas based on the environment or traffic conditions, which is an important feature for communication systems. The major objectives of beam shaping are to minimize pattern ripples, to reduce sidelobe levels, change null positions, or control output power levels, etc. Again this important feature can be controlled through the use of phase or time delay based controllers.

CRITICAL FEATURES OF PDL

Of critical importance to high precision military applications and systems such as high time-bandwidth product analog optical signal processors and delay lines for wideband RF systems is the ability to generate *long delays* with *low intrinsic loss*. As mentioned these two features are hardly accomplished with electronic approaches. One of the most successful techniques for obtaining long delay lines is the use of commercially available, single-mode (SM), low-loss, optical-fiber based technologies due to the large time-bandwidth product attainable with glass optical fibers. However, compactness, environmental robustness, manufacturing scalability and time delay precision are important, in particular for airborne applications where weight and size are very important.

To date, low loss optical fiber is the only guided-wave delay medium capable of providing these long delays with acceptable unamplified transmission loss. Nevertheless, size constraints, precise differential time delay control requirements and on-chip/off-chip optical signal routing complexity and management are some of the factors that have precluded fiber delay line processors from being more pervasive in military systems. Lithographically generated chip-scale, planar lightwave circuits (PLC) technologies offer the scalability and precision needed for implementing complex optical delay applications but they have limited optical delay performance due to the large propagation loss in optical waveguides. The best reported loss achieved to date in integrated photonic waveguides is on the order of 1 dB/m (compared to 0.3 dB/km for SM fiber), which translates to a delay/loss ratio of ~0.2 dB/ns (~200 dB/μs). These best integrated waveguide transmission losses are more than three orders of magnitude worse than optical fiber transmission, leading to insertion loss values that are unacceptable in most analog applications where signal-to-noise ratio (SNR) and dynamic range (DR) are critical. In general, optical amplification to overcome losses comes at a severe on-chip power, as well as SNR and optical bandwidth penalty.

The ability to realize “fiber-like” losses in a compact chip-scale, integrated photonic platform that can be readily integrated with passive optical, nonlinear optical, and active opto-electronic components is one of the real needs for the development of compact PDL systems. Today, these capabilities do not exist due primarily to the lack of an adequate integrated optical waveguide technology. The optical losses in state-of-the-art planar waveguides range from 0.1-1 dB/cm for semiconductor materials, less than 0.1 dB/cm for hollow-core waveguides, and as low as 0.005 dB/cm for flame hydrolysis deposited silica waveguides. While these losses have proved adequate for many commercial digital telecommunications applications, they do not support high spectral resolution optical signal processing simultaneous with high dynamic range signal detection. Since photonic links are lossy, the loss must be controlled and compensated so that the array amplitude taper is not unacceptably distorted. Note also that a 1 dB optical nonuniformity throughout the operation band produces a 2 dB RF nonuniformity.

In terms of time delay requirements, the longest time delay needed to scan an array of length L to θ_0 is $L\ sin\theta_0$. For example, a 100λ array scanned to 60° needs a longest delay of 87λ. With binary steps there would be 7 bits of time delay. Maintaining delays of 64λ, 32λ, and 16λ, to a small part of the least significant bit, is a challenging task. If the allowable error is 2, the time delay must be maintained to better than one part in 10,000.

RF performance and in particular linearity also plays a significant factor in microwave applications. Since photonic links are lossy, amplifiers must be used. The 3rd order Intercept Point (IP3), noise figure (NF) and spur-free dynamic range (SFDR) are a function of both the passive optical losses from the delay line structure as well as the electro-optic and optoelectronic conversion at the optical modulator and the optical detection module. Nevertheless, the RF performance of these components can be handled separately and we can focus on the optimization of the PDL in terms of optical insertion loss, time delay accuracy, inter-channel and intra-channel crosstalk, switching speed. Table 1 shows the typical requirements for an X band PAA as set by the RF engineers of the Lockheed Martin Corp (USA).

TABLE 1: PDL RF requirements

Parameter	Requirements
Number of Bits	7
LSB	0.1 ns
MSB	6.4 ns
RF Loss/bit	2.86 dB
Maximum time delay error	0.05 ns
Transmit to receive switching time	0.5 μs
Time delay setting switching time	0.5 μs
Frequency Range	X band
Interchannel crosstalk	<-60 dB
Intrachannel crosstalk	<-60 dB

PHOTONIC DELAY LINES

From the discussion in the previous sections, we can conclude that implementation of photonic signal processing and distribution techniques can significantly benefit PAAs. In this regard, PDLs provide a unique solution to implementing true time delay lines (TTDL) and hence overcome problems associated with beam squinting. It is the broadband nature of optical delay lines that enables beam steering independent of the RF frequency. Over the past two decades years, several optoelectronic technologies have been proposed for making variable PDLs. These techniques vary in their approaches and the optical technologies as depicted in Fig. 4.

The first to propose a passive multichannel fiber-optic delay line based on photodetector switching to select the desired time delay signal was Levine [13]. Instead of switching the detectors, Ng et. al. used electrically switched semiconductor lasers to implement the time delays [14]. The key limitation of this technique is the very large number of lasers, detectors, and associated hardware resulting in a relatively high cost, hardware-intensive system. An optical waveguide based switching network using integrated electro-optic switches for routing the optical signal into external single mode fibers was proposed by Soref [15]. A single channel 6-bit waveguide switching network was later implemented [16]. Other integrated optic approaches include electro-statically actuated metal membrane optical waveguide switches [17], and micro-machined meander-line thin-film piezoelectric micro-actuators for switching the light in different fibers [18]. Arrayed optical waveguides [19, 20], have also been used to form a wavelength dependant PDL.

Fiber delays have also been used to form non-switched photonic time delay networks. In this approach light is directed to predefined fixed length fibers to obtain the desired time delay [21]. A programmable binary fiber-optic (FO) delay line architecture was proposed by Goutzoulis [22] based on GaAs MESFETs for electrically switching paths between a non-delay electrical path and a delay FO path. The use of switched FO delay lines [23], where 2×2 cross bar electro-optic (EO) switches were used to switch paths of the optically modulated microwave signal was proposed. High interchannel crosstalk (leakage of signal through the switching fabrics to the undesired path) level was the key limitation of this approach. The use of independent (e.g., multichannel prism geometry) dispersive fibers with a single high power tunable laser source was proposed for making continuously variable (non-binary switching) PDLs [24, 25]. A similar approach has also been proposed, where instead of the fiber prism, a fiber with multiple Bragg gratings is used [26]. The above systems were limited only to transmit operation. In addition, the use of wavelength multiplexing has been proposed to reduce hardware in a photonically controlled phased array antenna that uses fiber delays [27].

Non-fiber based techniques have also been proposed for the implementation of time delay lines. A two dimensional (2-D) coherent optical architecture for time-delay-based PAA beamforming using free space delay lines was proposed independently by Dolfi [28] and Riza [29]. This interferometric architecture was based on polarization switching by two dimensional (2-D) spatial light modulators (SLMs) based on nematic liquid crystal (NLC) technology and free space propagation based delay lines using polarizing beamsplitters (PBSs) and prisms. The key limitation of this approach is the transmit only operation. Transmit and receive operation was demonstrated using multichannel PDL architectures based on 2-D SLMs that act as optical polarization switching elements. This approach is an incoherent reversible optical architecture

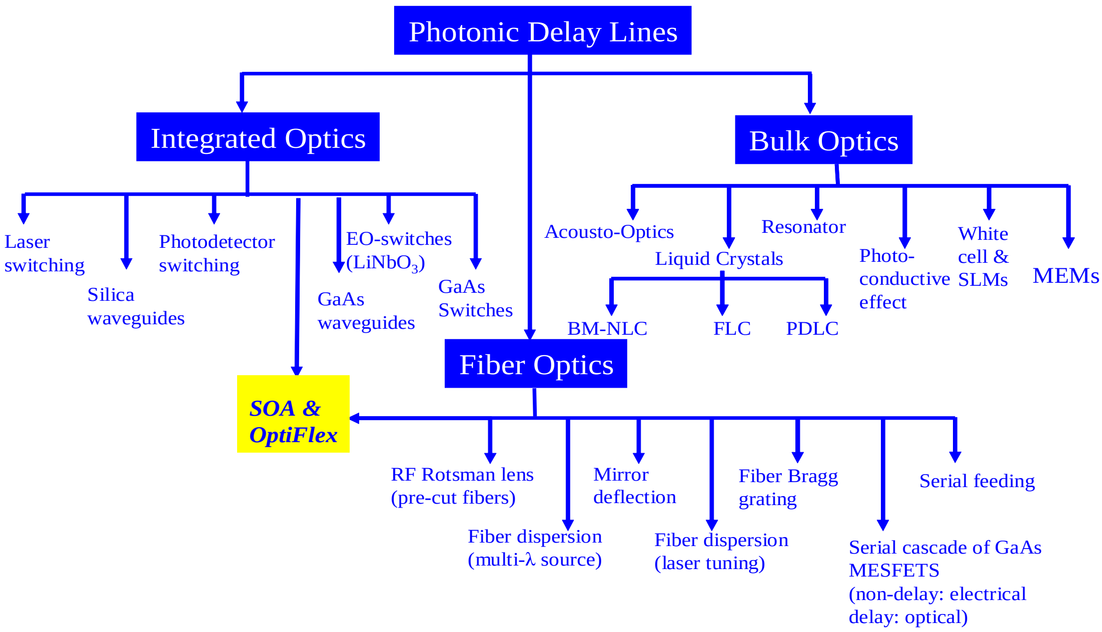


FIGURE 4. Classification of the different PDL approaches.

that uses 2-D polarization switching arrays. A single bit, 25-channel incoherent beamformer was demonstrated using NLC polarization switching devices at visible wavelength [30]. NLC devices are also limited in their switching speed (e.g., 10 ms). Finally, Ferroelectric liquid crystal (FLC) SLMs were used to built one of the most advanced PDL systems with 7-bit resolution and 32 channels, operating at 35μs response times and low insertion loss (e.g <1.2 dB/delay bit) [31].

Other optoelectronic technologies proposed for making variable photonic delay lines include polymer dispersed liquid crystal SLMs [32], thermo-optic switches [33], non-linear optical materials [34], acousto-optics [35], serial feeding and optical gating [36] and coherent detection methods [37]. Recently the use of the White cell in combination with SLM and or MEMS has been proposed for PDL applications [38].

LIMITATIONS OF EXISTING PDL APPROACHES

The PDL approaches presented in the previous section do solve some of the electronic controller imitations. Nevertheless, they do not fully satisfy all PDL performance requirements for wideband PAA control. Most optical switch fabrics can not provide the fast switching speeds (<0.5 μs) required in PAA control. Liquid crystal and MEMS based approaches are limited to milliseconds and at best several microsecond (e.g., Ferroelectric liquid crystals at 10 μs to 30 μs, [32-33]) speeds. Thermo-optic switches have been demonstrated at 45 μs switching speeds [39]. On the other hand, acousto-optic and non-linear optic approaches can provide higher switching speeds (e.g., <0.5 μs). Nevertheless, they have high insertion loss (e.g., $LiNbO_3$ ~5 dB, AO at ~1.5 dB). In addition, interferometric (i.e., Michelson interferometer) approaches using $LiNbO_3$ or Silica waveguides have poor on/off isolation performance, that directly affects the RF performance of the system. Besides the speed and loss issues, some of the aforementioned PDL approaches (e.g., AO) are rather bulky and can not be scaled down in size and weight as well as require high electrical power requirements undesirable for future PAA applications [40]. These features are increasingly becoming more and more relevant with the shift towards the use of PAAs in mobile platforms (e.g., aircrafts, satellites) where space and weight is of critical importance.

In order to accomplish high switching speeds and low insertion loss the use of SOAs as on/off switching elements in PDLs was proposed for PAA control [41] and later used to form a single channel PDL [42]. Optoelectronic integration techniques allow for the integration of multiple SOA elements on a single chip along with other passive optical components (i.e., passive optical splitters, filters, taps) and photodetectors. Real estate of the switching functionality can be minimized through this opto-electronic integration.

In many broadband applications long time delays (e.g., several ns) are required. To accomplish such delays long length fibers, high refractive index optical paths, or recirculating waveguide loops can be used. To this day, long fiber delays often exhibit the problem of accurately controlling the length and in particular when multiple channels are used. For given fabrication technology, optical waveguides with high index contrast materials exhibit high scattering loss and require very low roughness to achieve low loss waveguide which is a very difficult task [43]. Recirculating waveguide loops also exhibit high overall insertion loss due to the long propagation length in the high index material.

Recently the use of photonic crystals [44, 45] or photonic crystal fiber [46, 47] approaches have been investigated for the implementation of short physical length but long time delay PDLs through the high index of refraction capabilities of these material structures. Nevertheless these structures still perform with high insertion losses and maximum time delay at the picosecond (ps) or a few nanoseconds (ns).

SEMICONDUCTOR OPTICAL AMPLIFIER BASED SWITCHED PDL WITH OPTIFLEX CIRCUITS

In order to accomplish fast switching speed, low loss PDLs, with the required time delay bit accuracy the most promising technology is the one that is based on semiconductor optical amplifiers (SOAs). SOAs can perform two functions:

(a) optical switching and

(b) signal gain.

At the same time the physical implementation of the time delays is performed through the low loss glass fiber (0.3dB/mk) in an Optiflex circuit. Before we describe the architecture of the PDL we will provide some background information for the SOA and Optiflex technologies.

Semiconductor Optical Amplifiers

A SOA is a semiconductor diode chip in which indium phosphide (InP) is used as substrate material and indium gallium arsenide phosphide (InGaAsP) is the active material [48]. Electron-hole pairs are injected into the active layer, then recombine, emitting light. SOAs are fabricated using the same processing technology as that used for semiconductor lasers. This process has been used for many years and with high-volume production, so it is now well understood and highly reliable.

An SOA is essentially a laser that is operating under threshold. Whereas the laser requires some internal or external reflection for feedback, the SOA is a single-pass device. The input signal is usually coupled via a lens to the chip waveguide and the amplified signal exits the chip through another lens and into the fiber. Because of the high single-pass gain (>30 dB) of the active layer, reflections at the facets of the device are minimized ($<10^{-4}$). This eliminates optical feedback, which causes gain ripple. Optical isolators are often used to reject back-reflected light from the system.

The gain wavelength can be tailored from approximately 1.0 to 1.7 μm by varying the composition of the active InGaAsP material. This results in amplification of light in a wavelength region ranging from 1.28 up to 1.65 μm. It should be noted that the wavelength at the maximum gain and the optical bandwidth of the SOA are design parameters offering flexibility in applications. By changing the bias current of the SOA, the device can be either absorbing (low current) or amplifying (high current). This particular property of the SOA can be exploited in a PDL network to provide the required ultrafast switching response for high end PAA applications. The SOA can be operated as optical blocker, for example in the absorbing (or blocking) state it blocks the optical signal for propagating further down the network through the desired path, while in the amplifying (or non-blocking) state, it allows for the signal to go through the next PDL bit through the desired path. The high extinction ratio of up to 50 dB and the fast response time (ns) allows the SOA to be used as an optical gate in routing and/or packet switching [49, 50]. Operating SOAs as optical blocker in a PDL network can also provide the ultra-fast switching response required in high end phased array antennas applications.

Optiflex circuit technology

As mentioned earlier, a variety of approaches have been used to implement photonic delay lines. Free space, bulk (glass) optics, waveguides and/or fibers have been used as a medium for acquiring the required delay. High index materials in PLC configuration as well as optical fibers are of particular interest in long time delays. Nevertheless, although PLC techniques provide excellent differential control of the delay line accuracy, it is rather difficult to accomplish low loss long delay (e.g., a few ns) lines as those required for wideband PAA. On the other hand, most fiber approaches have not adequately address the limitation of accurate control of the length of individual fibers to a precision of a few millimeters (mm), and in particular over a large number of fibers, as required in fiber arrays. This can have implications of increased assembly time and rework until the required relative delay between the non-delay and the delay path is obtained. Furthermore, fiber management of complex fiber runs present challenges in the physical design and packaging and can be particularly labor-intensive and time consuming.

A technique of accurately forming these fiber based delays that can provide the low insertion loss and the long time delay is the OptiFlex circuit technology [41, 51, 52]. In conjunction with SOA as switches, Optiflex-based PDL is a unique technology that can adequately address the stringent time delay requirements of PDLs. The concept of the OptiFlex technology was invented and developed to form arbitrarily complex fiber-optic fabrics capable of transporting optical signals between termination points in optical network equipment with almost negligible loss [53].

The OptiFlex technology can be used to lay multiple fibers on a piece of plastic laminate sheet, providing low loss distribution, compact, flexible overlays. The process is very accurately controlled, via automated equipment, and is used to design, construct and terminate a flexible optical fiber fabric that is used as a board, backplane or other interconnection assembly [54]. The technology uses sequential layering of planar processes to allow the application of successive operations to build a circuit of optical fibers along the vertical axis [55]. Note that the manufacturing automation can lead to cost effective manufacturing and assembly efficiency similar to the ones in semiconductor and PCB industry. Optiflex was developed to address problems associated with the manufacturing and assembly of dense optical networks and particularly the interconnection of optical backplanes. Hence, it provides sets of fibers with a designed relative path length difference to allow time delays from the *ps* range to *μs* or more. Fig 5 shows a typical OptiFlex circuit previously used for optical back-planes.

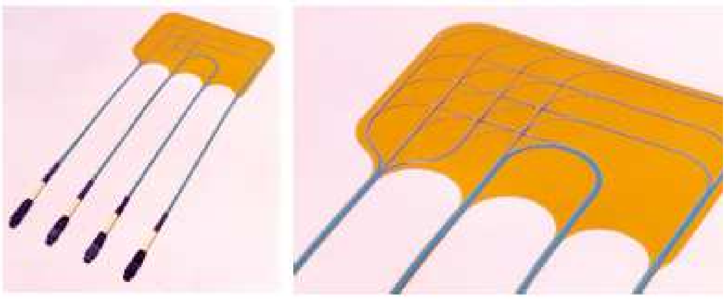


FIGURE 5: The OptiFlex technology previously used for optical back-planes in optical networks. (Courtesy of W. R. Holland, OFS Fitel, Somerset, NJ.)

The great advantage of this technique is that it can provide all the required PDLs on a single fiber circuit at small size and in a very compact and well organized configuration. Note that fiber pigtails coming out of the sheet can be ribbon type fiber, and ribbon fiber splicing can be used to interconnect to the SOA based photonic switch fabric and thus guaranty accurate relative optical path lengths. Note that potential deleterious effects such as crossover that can cause micro-bending losses are minimized in the Optiflex circuits by the use of special laminating techniques used to distribute the applied pressure on the thermoplastic encapsulant without concentration at the crossovers. Optical loss tests have shown no significant attenuation due to micro-bends [56]. Note also that new fibers developed for fiber-to-the-home (FTTH) access networks, designed for sharper bends with low loss can be used to accomplish more compact designs [57].

SOA/Optiflex-based Switched PDL Architecture

The basic schematic of the low-loss, high switching speed, SOA-switched PDL is shown in Fig. 6. A network of elemental PDL bits (Fig. 6a) will be used to implement the PDL system (Fig. 6b) for PAA control. Two PDL bits are shown for simplicity in Fig. 6a. Signal coming into Bit *N* is split into two replicas. One follows the top optical path that is connected to the Optiflex delay, while the other one can follow the lower part that follows the integrated waveguide path, which defines the non-delay path. The SOAs in each path can either be in their ON (transmissive) or OFF (blocking) state. The two SOAs always work out of phase, that is, when one is ON the other is OFF. Hence, each replica signal can be routed through the PDL bits independently of each other. Unbalanced Mach-Zehnder interferometers (MZI) are used as optical filters to suppress ASE from the SOAs operating in the on state. In addition, variable optical attenuators (VOAs) are used to control/adjust the optical powers in each arm so that the signal optical powers are balanced when they enter the next stage.

Fig. 6(b) shows a 7-bit PDL network for a PAA consisting of *N* antenna elements. Wavelength division multiplexing (WDM) techniques are used to combine and/or separate optical signals at different wavelengths so that hardware compression can be accomplished.

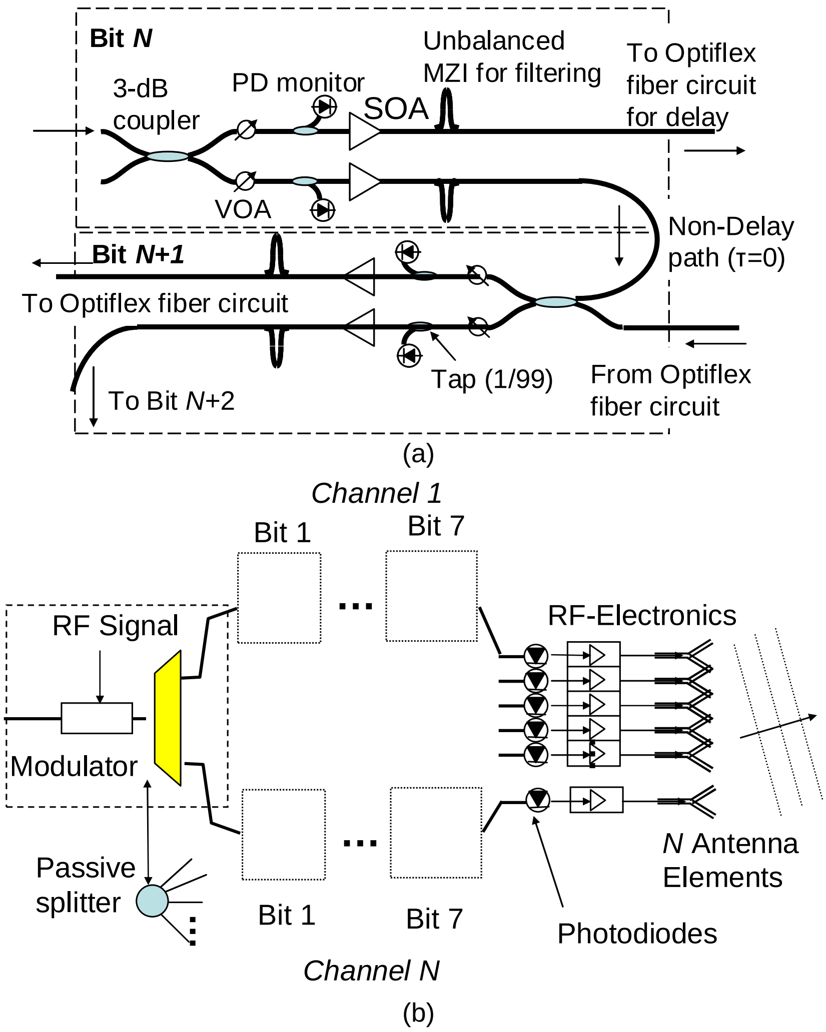


FIGURE 6. (a) Physical design of the elemental PDL, (b) The PDL system consisting of *N* 7-bit Delays addressing *N* antenna elements.

Signals from individual lasers (or multiwavelength laser-MWL) are demultiplexed through a WDM demultiplexer (DEMUX) after passing through an electro-optic modulator, which modulates the signal at the required RF frequency. Note that the RF BW of the system is limited by the BW of the modulator and the photodetector and not by the PDL system (e.g., the individual optical components that comprise the PDL). Fig. 6(b) also shows an alternative approach using a single high power laser and a star coupler that splits the signal in many replicas. This approach can provide cost savings since a single laser source is required; nevertheless, higher insertion losses due to splitter can reduce the SNR of the system.

Firstly, SOA technology can provide very small packages for arrays of SOA elements. Optical integration techniques such as monolithic integration can be used to house several SOAs (e.g., 10-15) on a single package (5 cm × 2 cm). An alternative approach is to use hybrid integration with passive assembly that reduces cost and time of manufacturing [58]. Note that using silica on silicon based hybrid approaches additional optical elements, such as optical filters, can be integrated on the optical circuit. Integration of optical filters at the waveguide paths can be used to reduce ASE power traveling through the delay line network and saturating the SOAs. The SOA technology in combination with the small size of the OptiFlex-based fiber delay lines can lead to a small overall PDL network. Note that for small delay lines (e.g., ps, ns) the PDL design can be implemented all on the chip level and for cases where longer delay lines (e.g., μs) are required, and are not feasible on the chip level, OptiFlex technology can be used. A miniaturized 7 bit PDL or one individual channel is shown in Fig. 7. All active switching, optical splitting/combining, filtering and reference delays are performed on a PLC. Multifiber fiber pigtails bring the signal to/from fiber delays based on Optiflex technology. Note that spiral fiber routing can be implemented to allow for maximum reduction in real estate area. Note also, although not shown in Fig. 7, fibers can overlap and cross over without any signal degradation or loss.

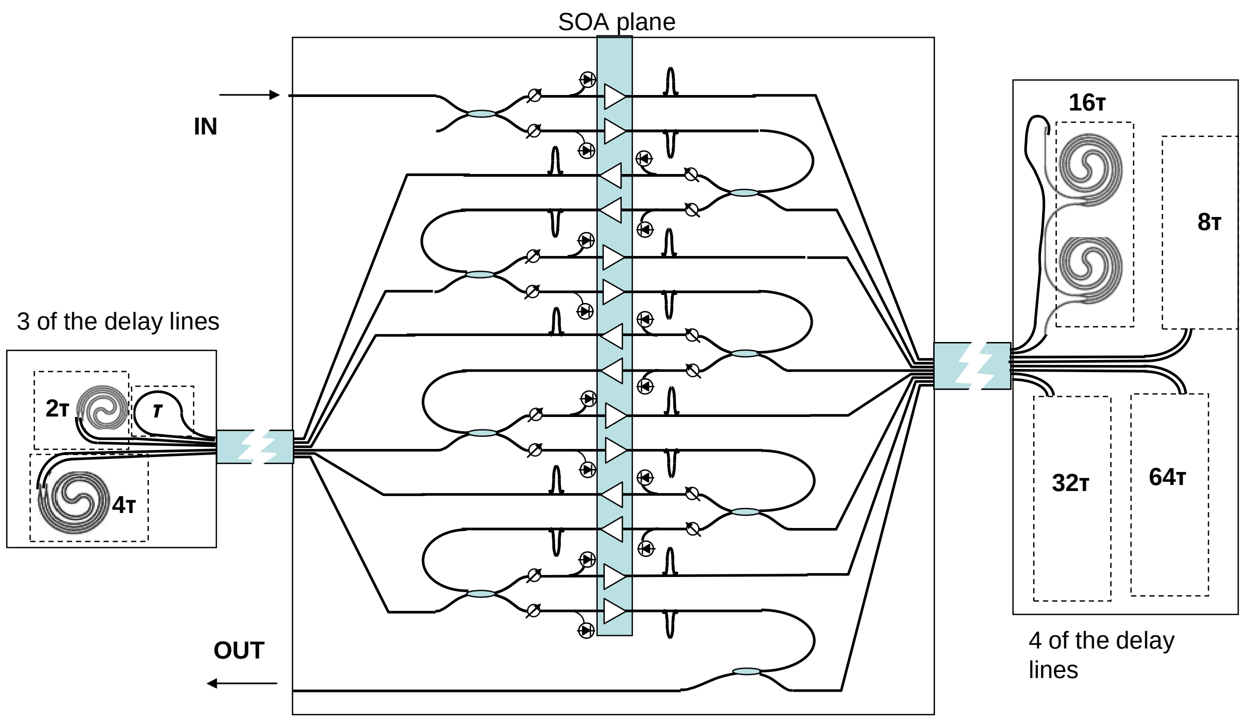


FIGURE 7. PDL architecture based on SOA switching circuits and OptiFlex fiber circuits.

Table 2: Required fiber length difference between the non-delay and delay paths of the PDL bit to achieve typical desired time delays.

Bit #	Delay (ns)	Fiber length difference (m)
1	0.1	0.02
2	0.2	0.04
3	0.4	0.08
4	0.8	0.16
5	1.6	0.32
6	3.2	0.64
7	6.4	1.28

Note that the required lengths of the optical fiber are not very long. For example for a typical PDL for PAA applications the time delay requirements are 0.1 ns to 6.4 ns (Table 1). Hence a relative path difference between the non-delay and the delay path from 2 cm to 1.28 m, respectively. Table 2 shows the required fiber length difference to achieve the desired time delays. That means that the fiber delays can be implemented in small Optiflex circuits. Note that Optiflex technology is transparent to the fiber used. These fibers can be high dispersion fiber, high bend radius fiber or any other fiber that can be designed to address a specific time delay requirement.

SYSTEM PERFORMANCE

In order to fully characterize the PDL optical but most importantly RF performance several studies are implemented. The study presented in this paper is focused on the

(1) Design of the physical dimension of the integrated SOA-switched PDL,
(2) Simulation of the performance of the proposed PDL, and
(3) Initial estimate of fiber length to meet the required delay lines, insertion loss (IL)
(4) Calculation of the PDL module, crosstalk and RF leakage noise.

The SOA response can be as fast as nanoseconds, and hence, it can provide the required switching speed with the minimum insertion loss and maximum on/off isolation. Insertion loss (IL) is a very important parameter for the design of a PDL, because it can directly affect the DR and the SFDR of the overall system. An additional advantage of using SOA elements in the PDL design is the potential to operate as optical amplifiers. Since optical components can introduce optical loss, individual SOA elements can operate at optimized gain in their transparent state (non-blocking state). Thus, SOAs compensate for the possible elemental losses. Moreover, using SOAs in the network the insertion loss budget can be optimized. This allows the use of the optimum optical power impinging on the photodetector, which leads to optimized performance in terms of DR and SFDR, parameters that are important for the health of the PDL network.

Another important parameter for the performance of the PDL network is the crosstalk. There are two types of crosstalk that can impact the PDL network performance. The first one is the optical interchannel crosstalk or leakage noise (that leads to RF leakage noise). The other one is the optical intrachannel crosstalk.

The PAA requirement for the RF leakage noise is <-60 dB, hence an optical leakage noise of < -30 dB is required. As optical leakage noise or interchannel crosstalk we define the leakage of adjacent channels to the channel of interest. In our design, each channel, which drives an antenna element, is physically isolated from the adjacent ones. Thus each channel goes entirely through its own delay line and the system's interchannel crosstalk is non-existent. For the case of the PDL system of Fig. 6(b), where a WDM DEMUX is used to separate the wavelength channels, the isolation of the system depends on the filter characteristics, and in particular the isolation, of the WDM DEMUX. 40 to 50 dB isolation is typical in today's WDM DEMUX's. Furthermore, an additional optical filter at the output ports of the WDM DEMUX can further increase the interchannel isolation.

RF intrachannel crosstalk of <-60 dB is required for PAA control, hence an optical crosstalk of < -30 dB is required. As intrachannel crosstalk we define the crosstalk due to optical leakage of the signal of interest through unwanted paths that eventually recombine with the signal of interest. This crosstalk is generated due to the non-ideal isolation of the switching elements. This crosstalk can eventually recombine and beat with the signal on the photodetector causing deleterious effects. The high isolation of the SOA between its ON and OFF states can provide extinction ratios of up to 50 dB. Hence, the necessary isolation between the two possible paths of each delay element can be accomplished. Fig. 8 shows the number of crosstalk terms of a 7-bit PDL system similar to the one shown in Fig. 7. We assume signal optical power of 0 dBm at the input of the system and -3 dBm at the output. Note that the most significant terms are 6 terms at -53 dBm, which is 50 dB lower than the signal. Looking at the worst case scenario of incoherent addition or accumulation of optical power of all crosstalk terms at the output a total power of -47.55 dBm is estimated that leads to an optical signal to noise ratio of 44.5 dB.

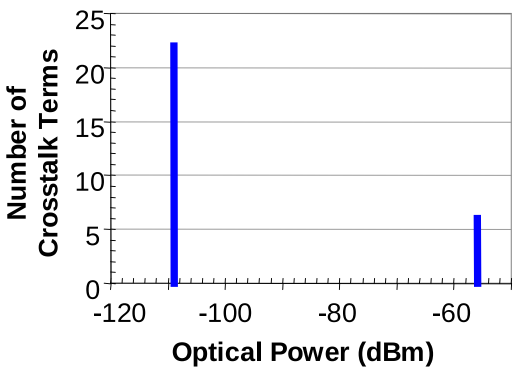


FIGURE 8. Optical power of the intrachannel crosstalk terms for the proposed 7 bit PDL. Maximum power of 6 terms is at -53 dBm.

The Optiflex technology allows for very accurate control of the fiber lengths. In particular the important issue is to accomplish accurate control of the differential delay between the non-delay and the delay paths, as well as among the PDL bits. If we assume a fiber index of refraction of 1.47, for an error of 1 mm in the relative difference of the optical paths the delay error is 0.0049 ns. This is much smaller than the required delay accuracy. Note that with the current Optiflex technology, accuracy of 0.5 mm or better can be accomplished and hence a delay error of 0.0025 ns or smaller is expected.

As was described earlier the SOA operation will have as an effect the generation of ASE noise. We will use optical filters to reduce ASE noise beyond the band of the transmitted optical wavelength and the associated spectral broadening due to the RF frequency of operation. Nevertheless, some of the ASE, passing through the optical filter may affect the noise level and hence the dynamic range (DR) of the system. This is one of the most critical issues that needs further investigation through experiments. Proper selection of component loss, SOA gain and SOA noise figure is required in order to optimize the systems dynamic range. Note that fiber optic links that make use of EDFAs have been demonstrated and perform with very low relative intensity noise and are the preferred approach for high end analog fiber-optic link applications [59]. Note also that integrated versions of PDLs with low count of bits and/or channels and small time delays (in the ps), with the integration of EDFA [60] as well as cascaded SOAs [61] have been demonstrated.

CONLUSION

We have shown that PDLs technology is a powerful and important technology for implementation of wideband PAA controllers. They solve many of the limitations of electronic controllers and can provide the future, wide bandwidth, compact, lightweight and small size, PAA controller. The emphasis of this paper was on a solution that makes use of commercially available components developed for WDM application, namely the SOA and Optiflex technologies. SOA provide the fast switching speed and high On/Off isolation required, while the Optiflex technology provides the required time delays and time delay accuracy. Excellent interchannel and intrachannel isolation is accomplished and the SOA gain can combat the insertion loss of the optical components. Additional optical filter are required to minimize the effect of ASE noise in the dynamic range performance of the PDLs and further optimization can be accomplished by selecting the proper SOA gain set points and noise figure. Future work relates to the experimental demonstration of this PDL architecture.

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